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Title: The Reactor Neutrino Anomaly

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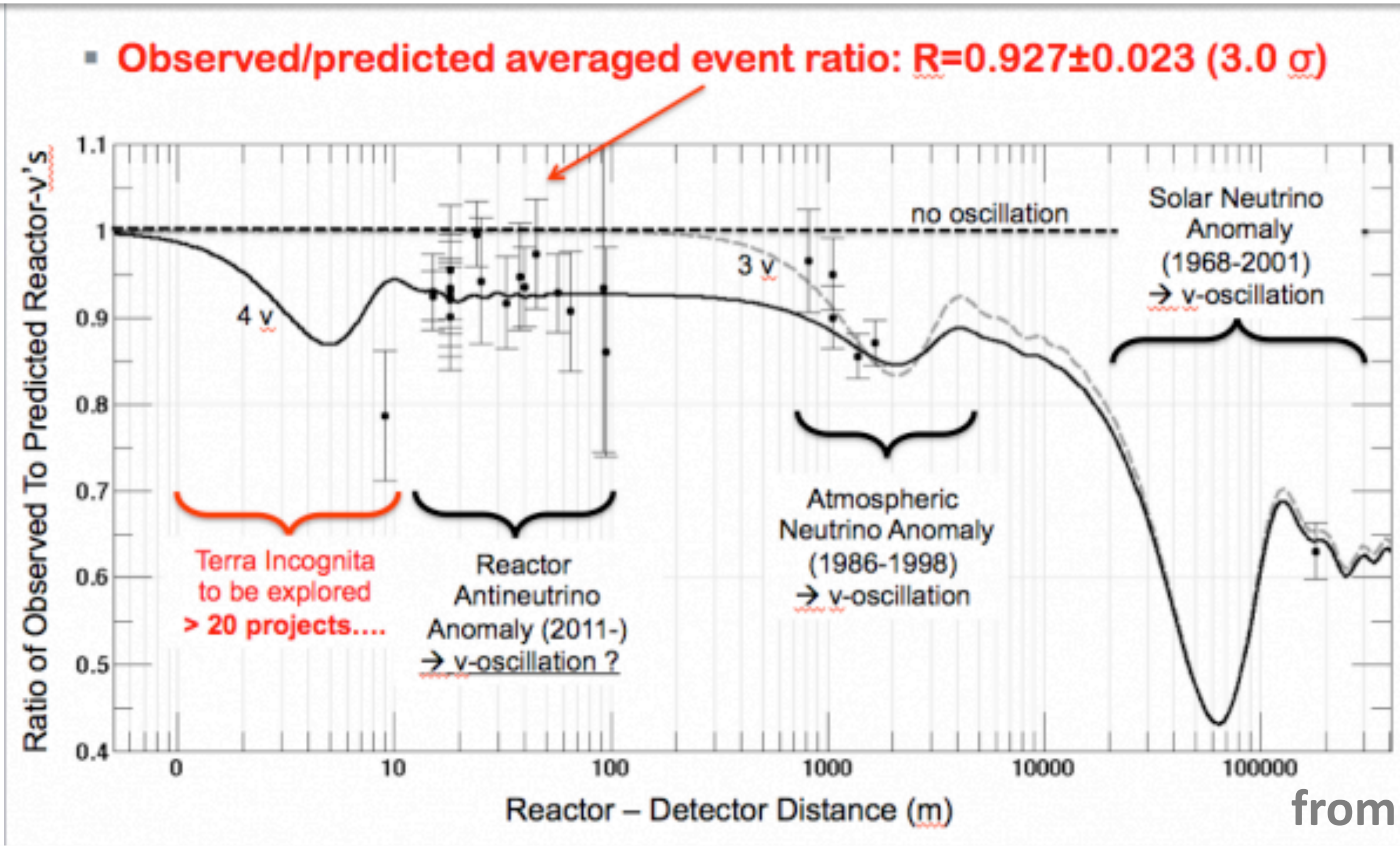
U. Wisconsin, 16th May 2013

The Reactor Antineutrino Anomaly

With Jim Friar, Gerry Garvey (LANL), Guy Jonkmans (Chalk River)



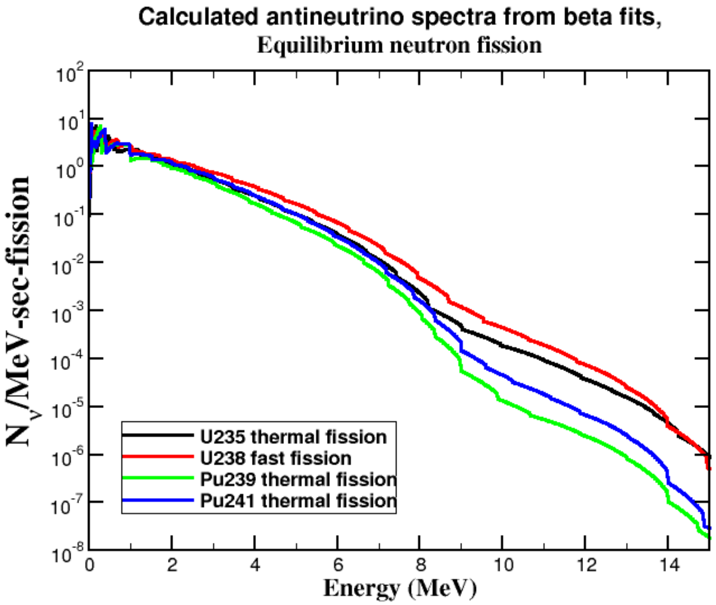
from Th. Lasserre

The effect mostly comes from the detailed physics involved in the nuclear beta-decay of fission fragments in the reactor

Intense Source of Neutrinos Emitted from Reactors

3 GW reactor emits about 10^{21} antineutrinos per second
- from the beta decay of the fission fragments

$$E_\nu \sim 0 - 15 \;\; MeV$$



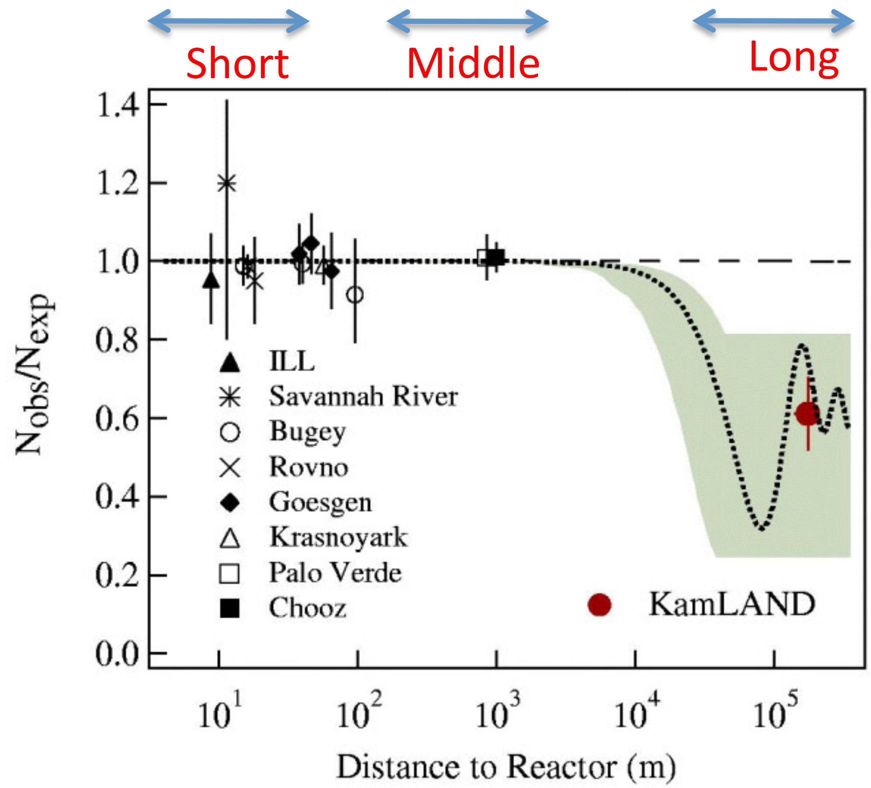
Detected by Reines & Cowan via:

$$\overline{\nu}_e + p \rightarrow n + e^+$$

Reactor Neutrino Experiments

Discoveries:

- Neutrino discovered in 1953-56 by Reines and Cowan.
- Short baseline expts determined antineutrino spectrum/flux (**????**)
- Upper limit of mixing angle θ_{13} to $\sin^2 2\theta_{13}<0.17$ (Chooz, Palo Verde)
- Anti-neutrino disappearance at KamLAND in 2003.



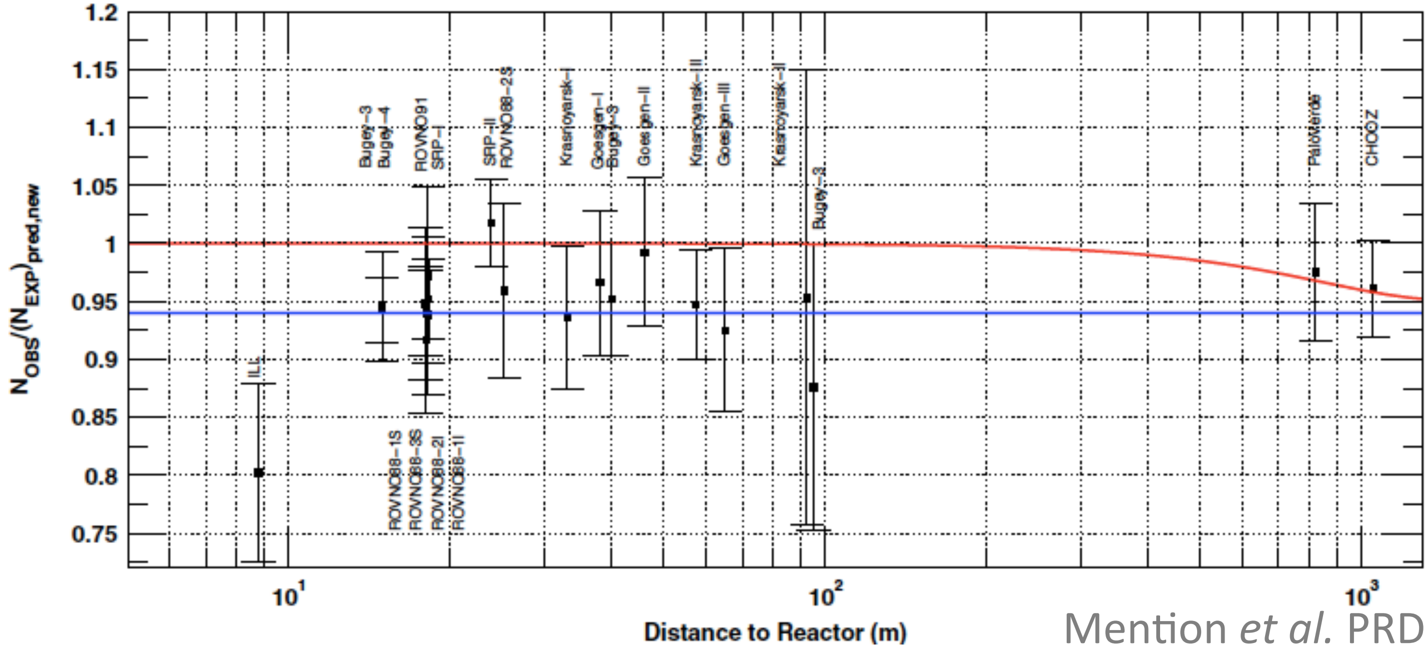
Current Experiments:

- Precision Experiments on θ_{13} (Daya Bay, Double Chooz, RENO)

Daya Bay: $\sin^2(2\theta_{13}) = 0.089 \pm 0.010(\text{stat.}) \pm 0.005(\text{syst.})$

RENO: $\sin^2(2\theta_{13}) = 0.113 \pm 0.015(\text{stat.}) \pm 0.005(\text{syst.})$

Short Baseline Reactor Anti-Neutrino Anomaly
Early Analysis Deficit 0.943, Current Deficit 0.927 (3.0 σ)



Mention *et al.* PRD 073006 2011

- A reanalysis of the anti-neutrino spectra from fission
- `Off-equilibrium' effects from long-lived fission fragments
- Correction to neutron mean lifetime

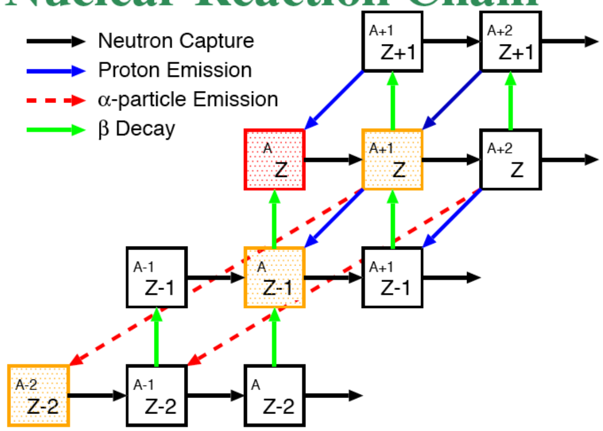
$\Rightarrow$ Average antineutrino signal observed/expected = 0.927+/-0.023

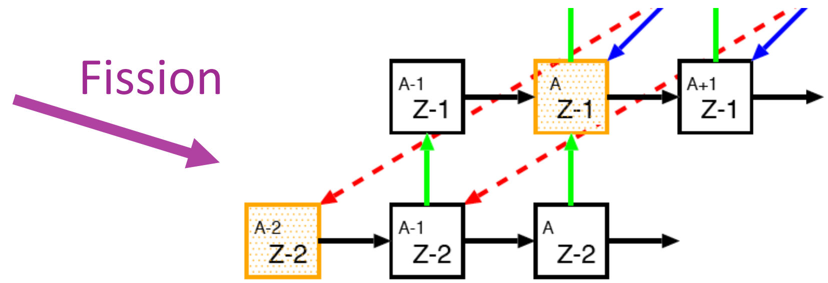
$\Rightarrow$ Disfavors no oscillation at 99.8% C.L. (with MiniBoone & Gallium)
$\Delta m^2 > 1.5\ eV^2$; $\sin^2(2\theta_{new})$=0.14+/-0.08 (95%)

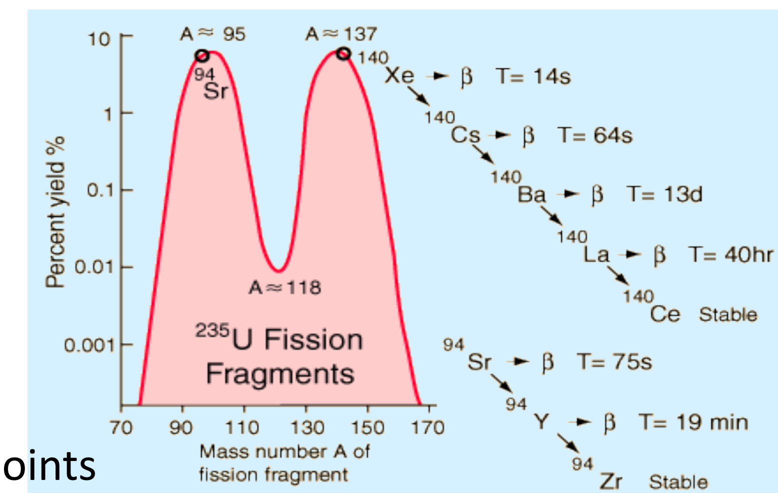
Over 100 other theory papers with non-standard model explanations

Beta Decay of Fission Fragments Produce Anti-neutrinos at a Rate of ~10^{20} ν/sec for a 1 GW Reactor

Nuclear Reaction Chain



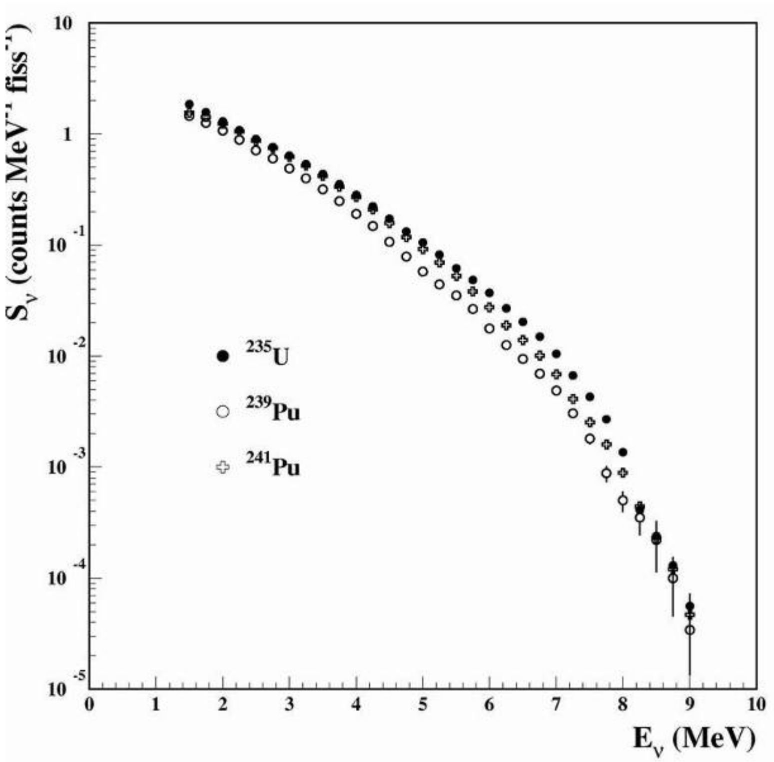




- About 1000 fission fragments – **neutron rich**
- Most fragments β-decays with several branches

$\Rightarrow$ About 6 ν_e per fission
$\Rightarrow$ Aggregate spectrum made up of thousands of end-points

The Antineutrino Flux used in Oscillations Experiments is from a Conversion of Aggregate Beta Spectra from ILL



- Measurements at ILL of thermal fission beta spectra for ^{235}U, ^{239}Pu, ^{241}Pu
- Converted to antineutrino spectra by fitting to 30 end-point energies, with one average Z=46 in calculating Fermi Function
- Use Vogel *et al*. ENDF estimate for ^{238}U ^{238}U ~ 7-8% of fissions =>small error

K. Schreckenbach et al. PLB118, 162 (1985)

A.A. Hahn et al. PLB160, 325 (1989)

FIT

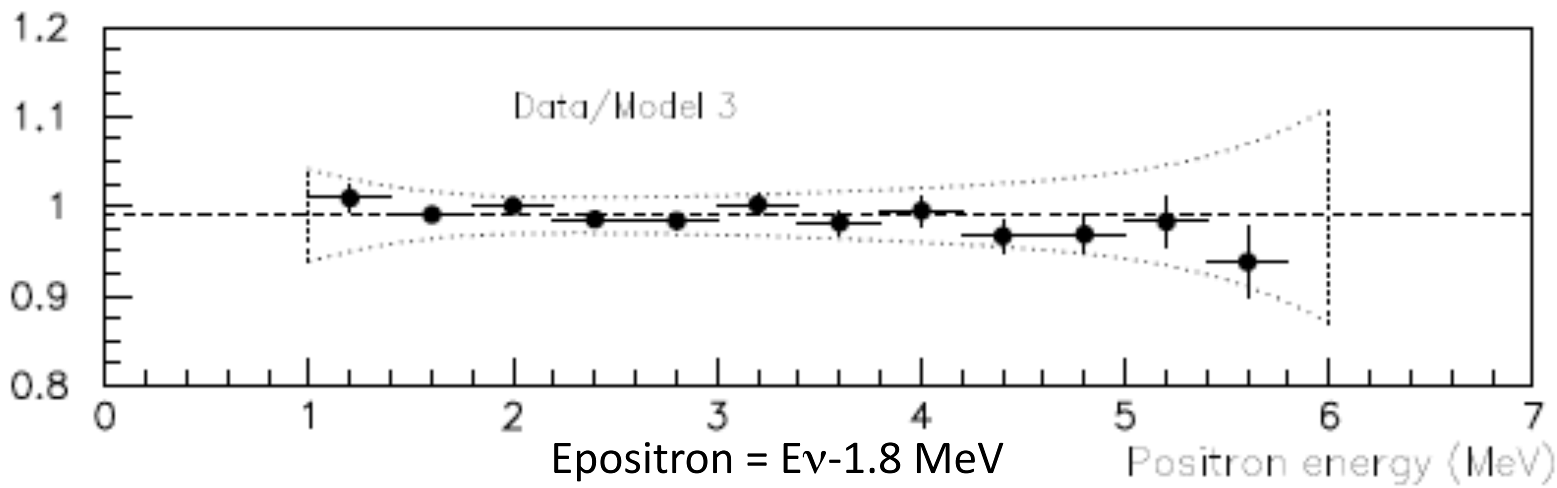
$$S_\beta(E) = \sum_{i=1,30} A_i S^i(E,E_o^i)$$

$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E,Z)(1+\delta_{RAD})$$

Before the Anomaly

Bugey-3 measured antineutrino spectra 15 and 40 meters from reactor core

- No evidence for oscillations
- Validated ILL measurements by Schreckenbach et al.

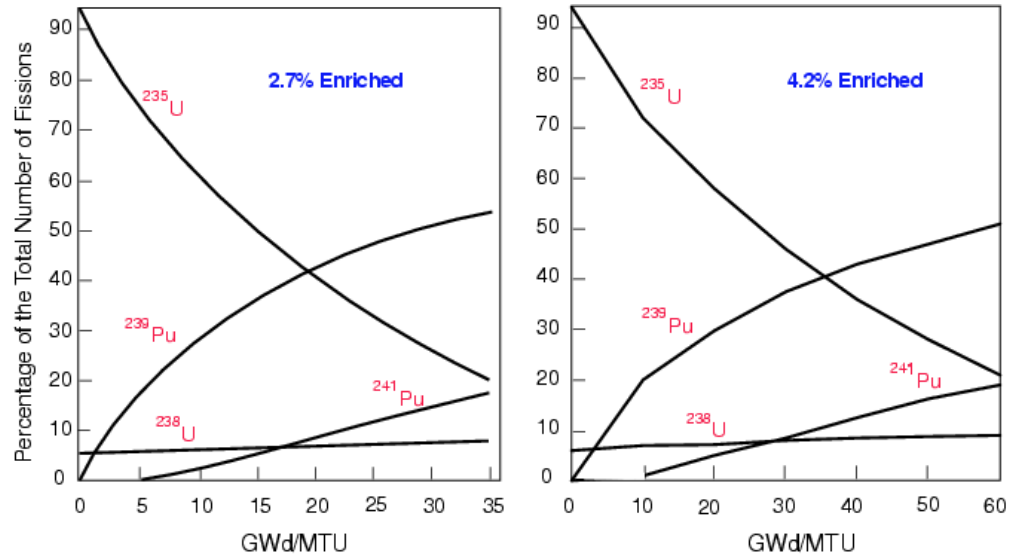


Epositron = Eν-1.8 MeV

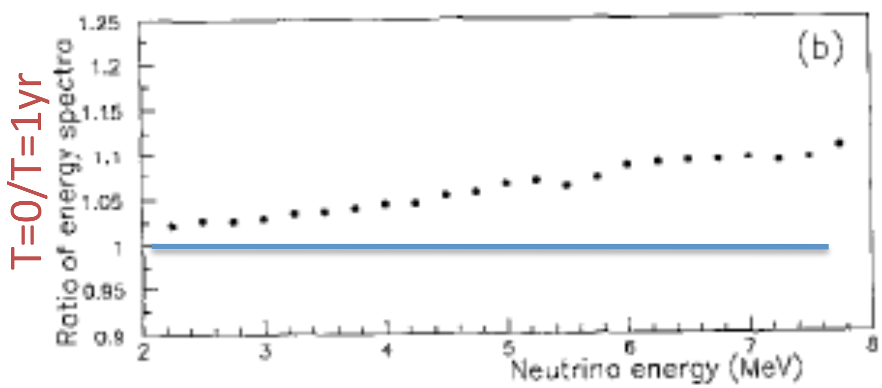
- Uncertainty in antineutrino spectra per fission < 2%

As Burn Proceeds: Different Combination of Isotopes Fissioning

^{239}Pu steadily grows in via:
$^{238}U+n \rightarrow {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$
Followed by higher mass Pu



This change translates into a change in the antineutrino spectrum emitted from the beginning to the end of a burn cycle



Bugey-3 energy-dependent decrease after 1 year

⇒ 5% fewer detected antineutrinos after 1 yr
⇒ Must be taken into account in osc expts.
⇒ Basis of non-proliferation schemes

Calculating the Flux

1. Measure **thermal power** in primary & secondary loop
W_{th} uncertainty ~<2%, but KamLAND quote 0.6-0.7%
Uncertainty usually dominated by water flow measurement.

$$N_f = W_{th} / E_f$$

$$E_f = E_{tot} - < E_\nu > - \Delta E_{\beta\gamma} + E_{(n,\gamma)}$$

2. Calculate **number of fissions** from W_{th}
Uncertainty in N_f ~ 3% quoted by AECL
E_f good to ~0.5-1%
Kopeiken et al. Phys. Atom Nucl. 67 (2004) 1892

$$S(E_\nu) = \sum_i^{isotopes} f_i S_i(E_\nu)$$

3. Reactor **burn simulation** to determine
what isotopes are fissioning Uncertainty ~ 2-3%, as low as <1%

4. Knowledge of **individual antineutrino spectra** for each fissioning isotope
Mention collaboration ~ 3% but shifted by +3%; Huber finds larger increase
Mention *et al.* PRD 073006 2011 & Mueller et al. PRC 83 (2011) 054615
Huber PRC 84 024617 (2011)

Reanalysis of Conversion from Beta to Antineutrino Spectra

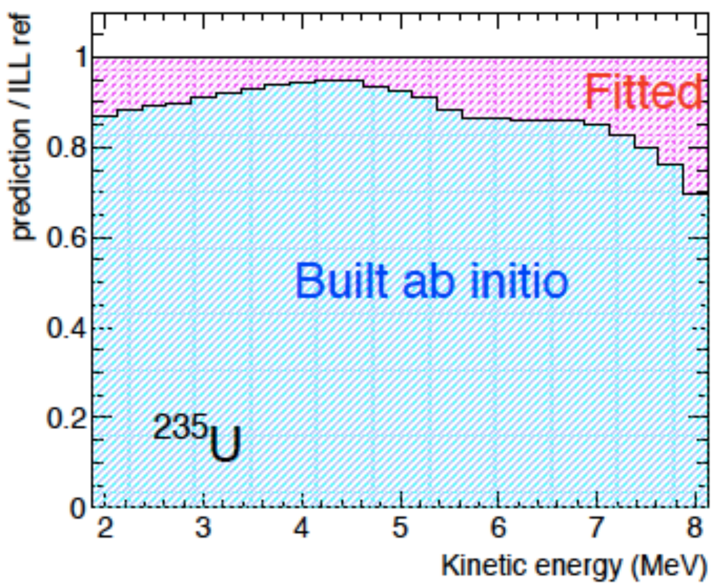
- Main source of the "Reactor Neutrino Anomaly"

Th. Mueller arXiv:1101.2663; G. Mention PRD 83 (2011) 073006

FIT ~ 15% unknown

$$S_\beta(E) = \sum_{i=1,known} Y_{ff}\, S^i(E,E_o^i) + \sum_{j=1,30} A_j S^j(E,E_0^j)$$

$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E,Z^i)\,(1+\delta(E,Z,A))$$



Use correct Z, if known

Add known corrections to beta decay spectrum

- Finite nuclear size corrections
- Weak magnetism

Correct for "non-equilibrium" contributions

Correction from neutron lifetime

Allowed Beta-decay & Corrections

$$S(E_e,Z,A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 F(E_e,Z,A)(1+\delta(E_e,Z,A))$$

Fractional corrections beyond leading order:

$$\delta(E_e,Z,A) = \delta_{FS} + \delta_{WM} + \delta_R + \delta_{rad}$$

δ_{FS} = Finite size correction to Fermi function

δ_{WM} = Weak magnetism

δ_{R} = Recoil correction

δ_{rad} = Radiative correction

Omitted in analysis of Schreckenbach *et al.*
Main source of the anomaly

The Finite Nuclear Size Correction

Normal (point-like) Fermi function:

Attractive Coulomb Interaction *increases* electron density at the nucleus

=> beta-decay rate *increases*

Finite size of Nucleus:

Decreases electron density at nucleus (relative to point nucleus Fermi function)

=> Beta decay rate *decreases*

Two contributions: nuclear charge density $\rho_{ch}(r)$ and nuclear weak density $\rho_W(r)$

$$\boxed{\delta_{FS} = -\frac{3Z\alpha}{2\hbar c} < r >_{(2)} \left(E_e - \frac{E_\nu}{27} + \frac{m^2c^4}{3E_e}\right)}$$

$$< r >_{(2)} = \int r\, d^3r \int d^3s\, \rho_W(|\vec{r} - \vec{s}|)\ \rho_{ch}(s)$$

-First moment of convoluted weak and charge densities

= 1st Zemach moment

The Weak Magnetism Correction

The interaction with the nuclear magnetic moments *increases* the electron density at the nucleus => beta decay rate *increases*

$$J_V^\mu = \left[Q_V,\ \vec{J}_C + \vec{J}_V^{MEC} \right]$$

Affects GT transitions

$$J_A^\mu = \left[Q_A + Q_A^{MEC},\ \vec{\Sigma} \right]$$

Equivalent correction for spin-flip component of forbidden transitions

$$\boxed{\delta_{WM} = \frac{4(\mu_V - \tfrac{1}{2})}{6 M_N g_A}(E_e \beta^2 - E_\nu)}$$

Corrections for GT Transitions

1. Finite size of the nucleus

Vogel: (approximate)

$$A_c = -\frac{10Z\alpha R}{9\hbar c} E_\beta \;;\; R = 1.2A^{1/3}$$

Friar, Holstein (*ab initio*):

$$A_c = -\frac{3Z\alpha R}{2\hbar c}\left(E_\beta - \frac{E_\nu}{27} + \frac{m_e^2}{E_\beta}\right);\; R = \frac{36}{35}(1.2A^{1/3})$$

2. Weak magnetism

Vogel: (approximate)

$$A_w = \frac{4(\mu_V - 1/2)}{3M_n} 2E_\beta$$

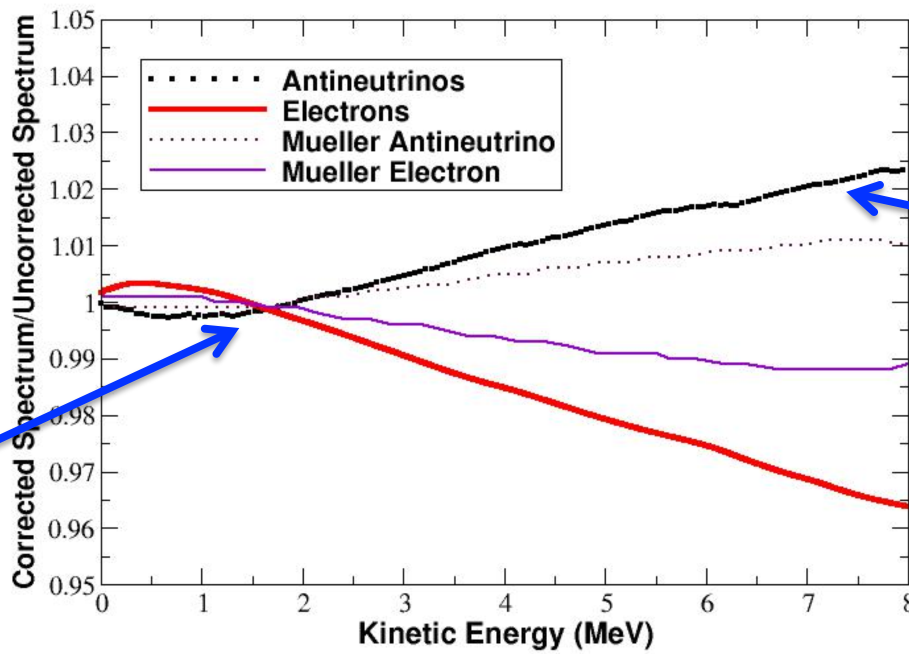
Friar, Holstein (*ab initio*):

$$A_w = \frac{4(\mu_V - 1/2)}{6M_n}(E_\beta \beta^2 - E_\nu)$$

First principles derivation of the corrections different from what was used

But ~ same magnitude

Effect of FS and MW Corrections to Spectrum using ENDF/B-VII, and <u>Assuming all Transitions are Allowed</u> Shows a Clear Anomaly



$\overline{E}_0/2$

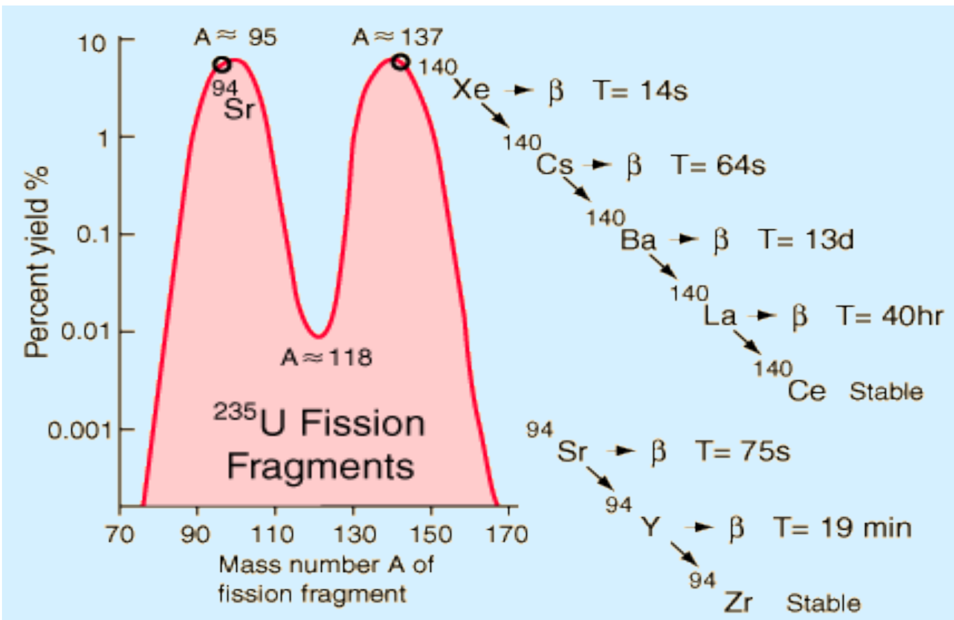
$$\cong \frac{1}{2}\left[\frac{4(\mu_v - \frac{1}{2})}{3} - \frac{3Z\alpha R}{2\hbar c}\right]$$

- Obtain larger effect & stronger energy dependence than Mueller
- (Approximately) similar to P. Huber

- Linear increase in the number of antineutrinos with En>2 MeV
- Slope well defined

Many Transitions at Both Peaks of Fission Yields are Forbidden

Forbidden means:
Not Fermi (0+) or GT (1+)
i.e, $\Delta L>0$, $\Delta\pi=+/-1$



A~95 Peak
Br, Kr, Rb, Y, Sr, Zr mostly forbidden
Nb, Mo, Tc often allowed GT

A~ 137 Peak
Sb, I, Te, Xe, Cs, Ba, Pr, La
 - mostly forbidden

The forbidden transitions tend to dominate the high energy component of spectrum
Branching ratios high, according to ENDF/B-VII Decay Library and ENSDF

Unique Forbidden versus Non-unique Forbidden Transitions

Allowed: Fermi τ and Gamow-Teller $\sigma\tau$

Forbidden: $\Delta L \neq 0\ ;\ \vec{\mathrm{L}} \otimes \vec{S}(=0)^{\Delta J = \Delta L}, \mathrm{L} \otimes S(=1)^{\Delta J = \Delta L \oplus 1}, \Delta\pi = (\text{-})^{\Delta \mathrm{L}}$

Unique if $\mathrm{L} \otimes S(=1)^{\Delta J = \Delta L + 1}$, e.g., 2^-

Unique transitions only involve one operator & there is a unique shape change e.g., 2- the phase space is multiplied by p^2+q^2

Non-unique transitions involve several operators & the p^2+q^2 correction may or may not be important – depends on nuclear structure details

Examples:

^{142}Pr $2^- \rightarrow 2^+$ nice allowed shape

^{139}Ba $7/2^- \rightarrow 5/2^+$ has a shape like unique 1st forbidden

Treating the Forbidden Transitions

1. Unique 1st Forbidden

Weak Magnetism (Friar)

$$A_W = \frac{6\mu_V}{10 M_n g_a}\left[\frac{(p_e^2 + p_\nu^2)(p_e^2 / E_e - E_\nu) + \frac{2}{3} p_e^2 (E_\nu - E_e)}{(p_e^2 + p_\nu^2)}\right]$$

Shape change

$$S^i(E, E_0^i) = (p_e^2 + p_\nu^2) E_e p_e (E_0^i - E_e)^2 F(E, Z)$$

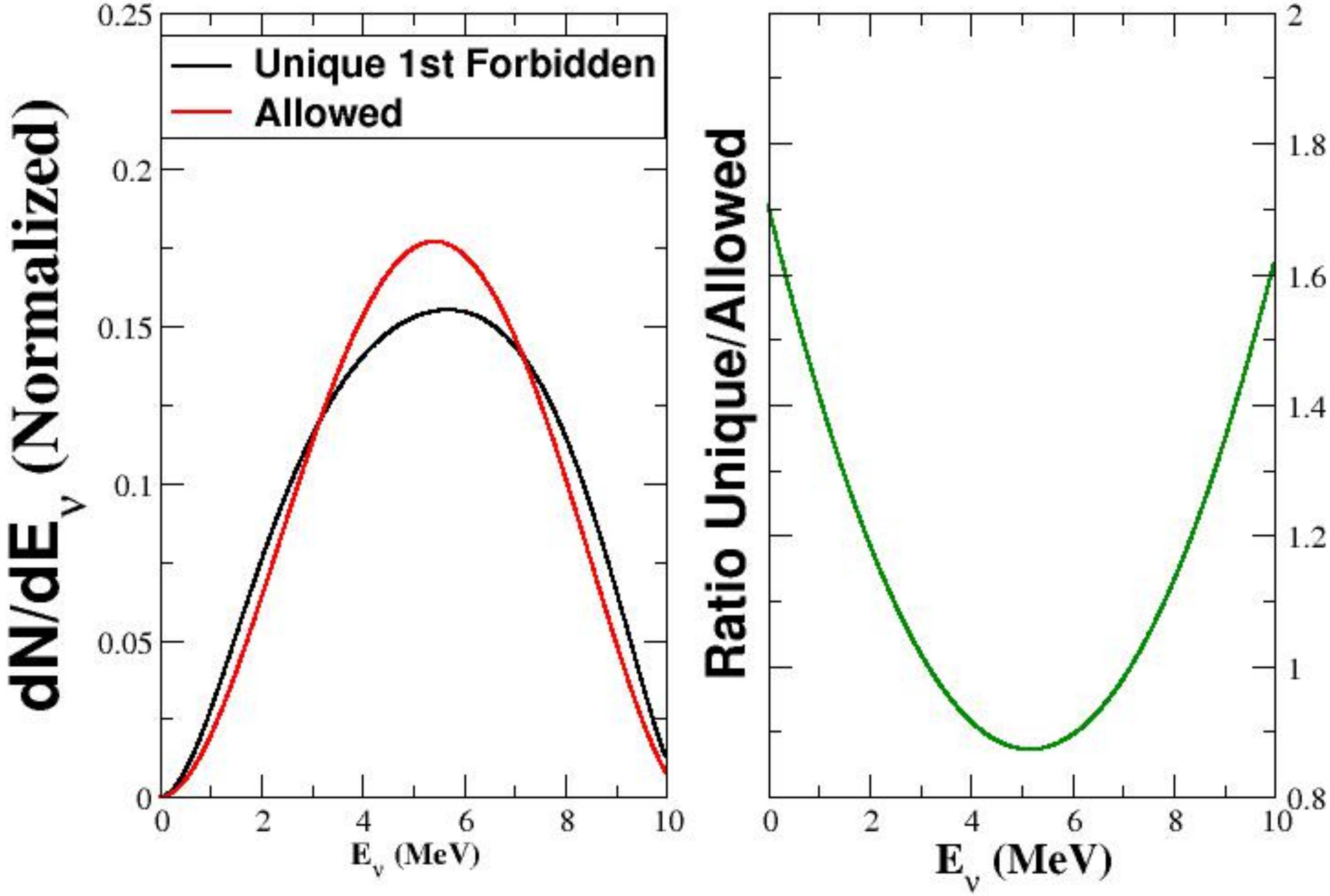
2. Non-unique Forbidden

– shape change is very nuclear structure dependent

Try different prescriptions

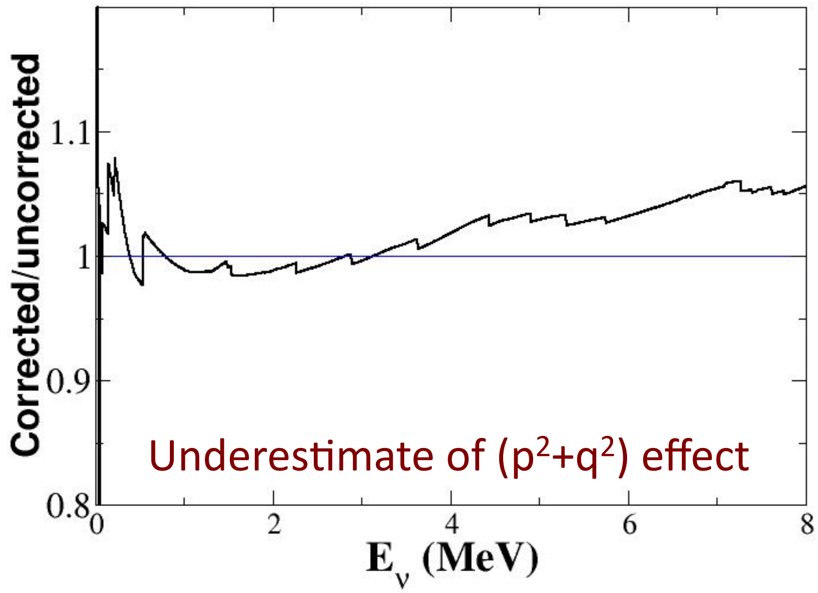
Same as allowed, same as unique, something in between

Correction Due to Forbidden Shape is Very Large
Suppresses Spectrum in Centre, Enhances it on either side

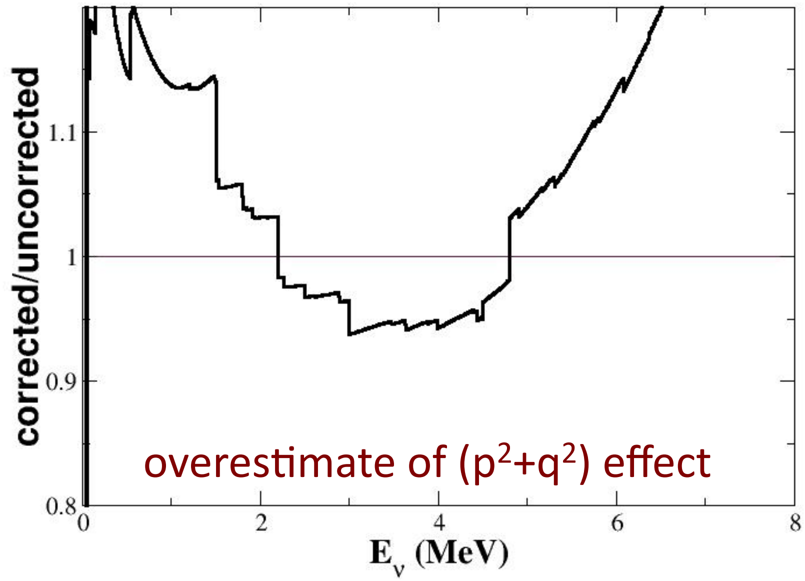


Treatment of Forbidden Transitions Significantly Changes the Shape of the Antineutrino Spectrum

New corrections for known unique
All other known forbidden = allowed
All unknown omitted

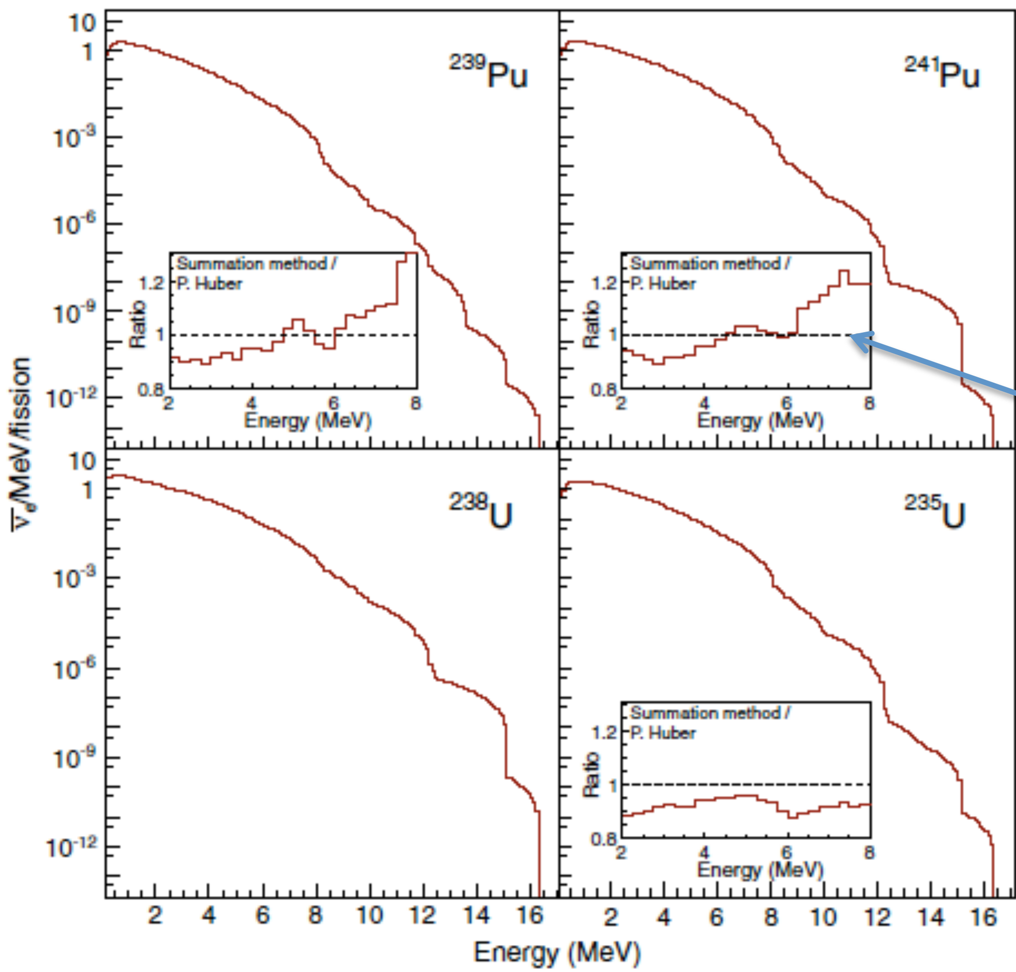


All known forbidden transitions and unknown treated as unique



In either case, role of forbidden transitions overwhelms the effects of weak magnetism or finite size corrections

Similar Shape change Seen in an Independent Analysis that Included Forbidden Spectral Shapes

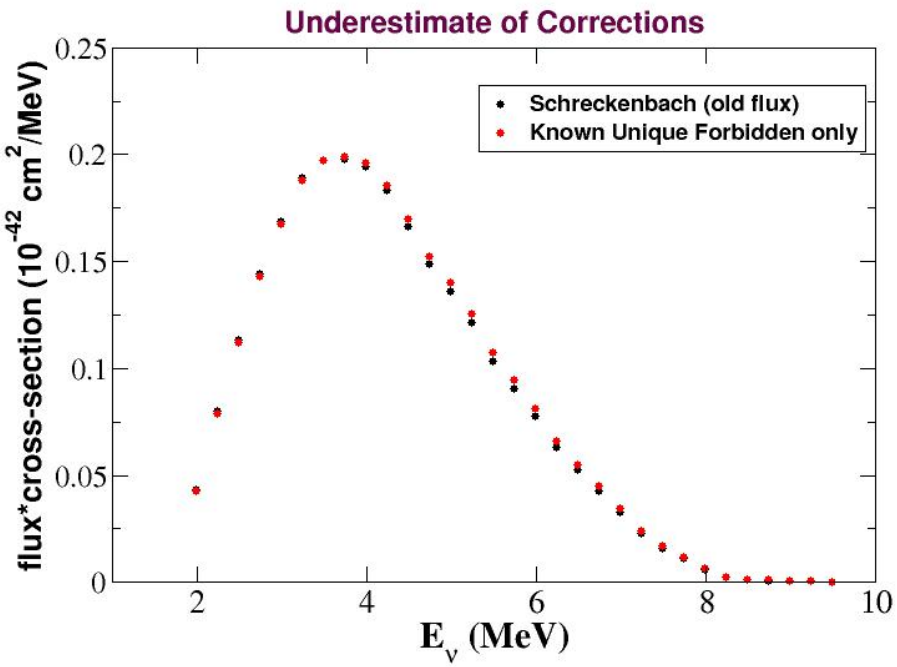


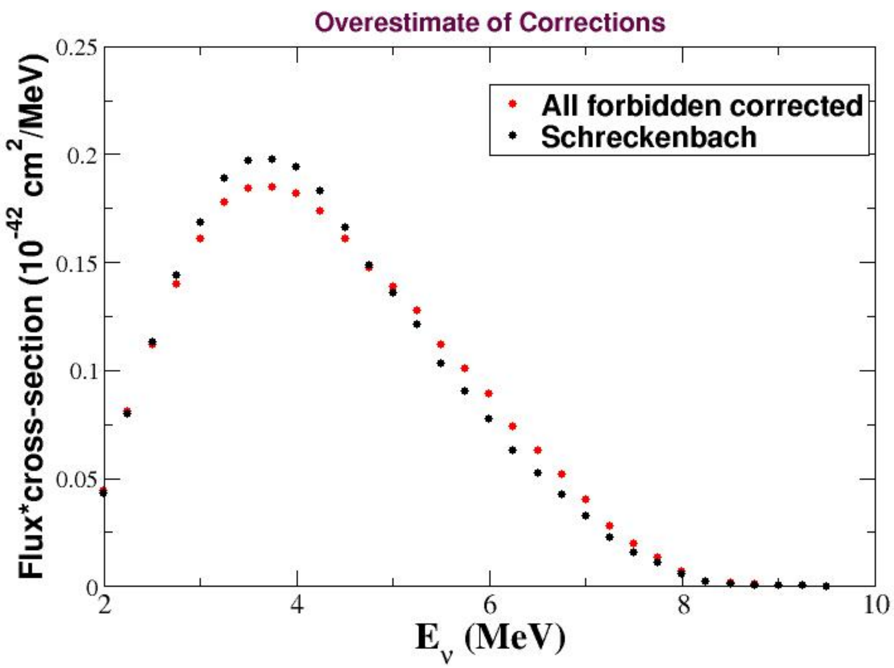
M. Fallot et al., PRL 109 202504 (2012)

Suppression at low neutrino energies
Enhancement at high neutrino energies

In this analysis all forbidden transitions were treated as unique
=> Likely to overestimate of shape change

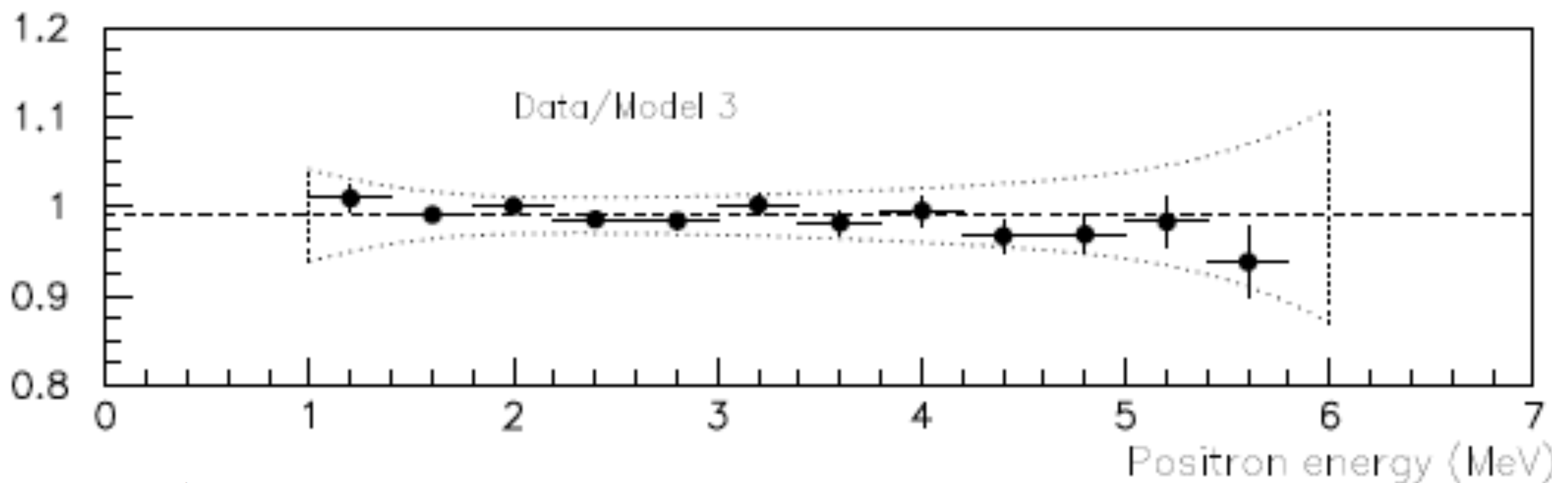
Apply Corrections to Expected Detection Signal
Known Unique only versus All Forbidden & Unknown



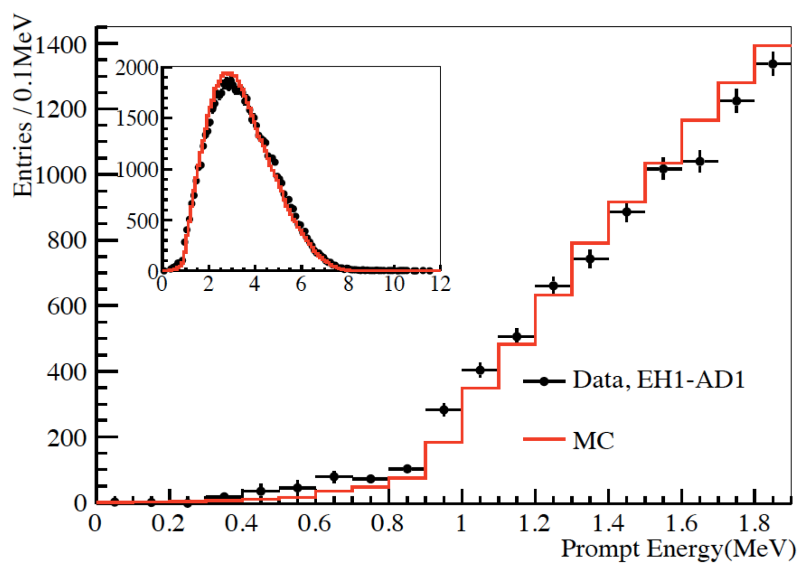


- In both cases see larger signal below about 2.5 MeV &above about 5.0 MeV
- Treat only known uniques as unique, no anomaly at peak, slight enhancement (5%) at 6 MeV
- Treat all forbidden as unique => ~7% suppression at the peak & 15% enhancement at 6 MeV
- Reality is somewhere in between these two limits

Bugey 3 Did Not See Excess above 5 MeV
Daya Bay seems to See Effects Consistent with Corrections ?



Bugey



Daya Bay

Ep =Eν + 1.8 MeV

Status of the Reactor Anomaly

- The weak magnetism and finite size effects are the main source of corrections that led to the anomaly
- These corrections clearly increase the antineutrino spectrum
- Forbidden transitions are 30% of the total
  - Lower the spectrum from 2.5-4.5 MeV – peak area
  - Increase spectrum at low (<2.5 MeV) and high energies (>4.5MeV)
  - Increase at high energies <u>not seen</u> in Bugey, for example
- Large uncertainty in how to treat non-unique forbidden transitions
  - Uncertainty outweighs the size of the anomaly, but excess still expected at high energies
- Requires high statistical measurement to reduce the uncertainties, for example, Daya Bay